NESC Review Board
Final Report Presentation

Treatment of Transient Pressure Events in Space Flight Pressurized Systems
NESC-PR-011-TP-06

Kauser Imtiaz, NESC Technical Fellow, Structures
Vinay Goyal, Technical Lead, The Aerospace Corporation

September 2, 2021

Key Stakeholders

The key stakeholders for this assessment include:

- **Commercial Crew Program (CCP) Engineering**
- **NASA Programs**
- **NASA Partners and Contractors**
- **General Aerospace Industry**

Team List

Name	Discipline	Organization
Core Team		
Kauser Imtiaz	NESC Structures Technical Fellow	LaRC
Vinay Goyal	Principal Engineer, Structures	LaRC/The Aerospace Corporation
James Smith	Structures, Deputy NESC	JSC
Pavel Babuska	Structures	LaRC/The Aerospace Corporation
Ethan Barbour	Propulsion/Fluids	The Aerospace Corporation
Consultants		
Gary Wang	Structures	JPL
Kenneth Hamm	NESC Chief Engineer at ARC	LaRC
Robert Wingate	Structures	MSFC
Dawn Phillips Price	Structures	MSFC
Mark Mueller	Principal Engineer, Propulsion	LaRC/The Aerospace Corporation
Business Management		
Catherine Little	Program Analyst	LaRC/MTSO
NESC Support		
Leanna Bullock	Technical Editor	LaRC/AMA

Acknowledgements

Case Studies:

- Sophonias Teshome (Fluids), The Aerospace Corporation
- Sean Engelstad (Structures), The Aerospace Corporation
- Frederick Golinveaux (Structures), The Aerospace Corporation

Consultations / Informal Peer Reviews:

- Alvar Kabe, Dynamics, The Aerospace Corporation
- John Klug, Structures, The Aerospace Corporation
- Erik Mellquist, Dynamics, The Aerospace Corporation
- Yenyih Ni, Structures/Propulsion, The Aerospace Corporation
- Nikolas Nordendale, Structures/Propulsion, The Aerospace Corporation
- Christopher Sagrillo, Structures/Propulsion, The Aerospace Corporation
- Brett Soltz, Structures, The Aerospace Corporation
- Phuong Than, Fluids, The Aerospace Corporation
- Ryan Tuttle, Dynamics, The Aerospace Corporation

Diverse multidisciplinary team (Structures, Fluids/Propulsion, Dynamics) was involved in development of position paper

Acknowledgements

Peer Reviewers:

- Jeffrey Bruggemann, Propulsion Systems Test Engineer/ Project Manager, WSTF
- Daniel Dorney, NESC Technical Fellow, Propulsion, LaRC
- Steven Gentz, NESC Chief Engineer, LaRC
- Michael Gilbert, NESC Principal Engineer, LaRC
- Carl Guernsey, Engineering Fellow, Propulsion, Thermal, and Materials Engineering, JPL
- Robert Jankovsky, NESC Chief Engineer, GRC
- Donald Parker, NESC Principal Engineer, LaRC
- David Schuster, NESC Technical Fellow, Aerosciences, LaRC
- Brian Steeve, Structures, MSFC
- Eugene Unger, ECLSS Systems, Retired, JSC
- Jeffery West, Fluid Dynamics Branch, MSFC

Introduction

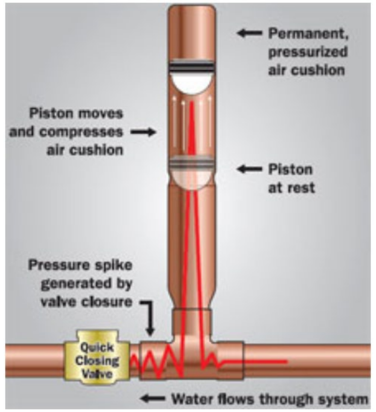
- CCP Chief Engineer requested position on how to treat pressure transients in spaceflight hardware
- Position paper developed to provide guidance on the treatment of pressure transients
  - Provides clarity amongst the various standards (AIAA, NASA, SMC) on acceptable methods to include or assess pressure transients
  - Introduces methods for pressure transient behavior (pulse shape, duration, magnitude)
  - Provides guidance on addressing the dynamically induced stress response for pressure system components
  - Discriminates between treatment of pressure transients for Pressure Vessels vs. Pressure Components (lines, fittings, etc.)
  - Provides certification guidance
    - Strength based – adjust either Maximum Expected Operating Pressure (MEOP) or proof/burst factors to account for pressure transients
    - Damage tolerance based – account for transients in life analysis while utilizing nominal proof/burst factors

Background

- Pressure transients must be predicted or measured accurately to properly design a pressurized system
- Pressure transients have resulted in system failures and structural failures due to inadvertent overload or fatigue with failures being well documented in oil, chemical, civil, and nuclear industries
- Common sources of failure are as follows:

1. incorrect assumptions in transient pressure analysis that did not include worst-case operating conditions
2. insufficient design evaluation of elements vulnerable to high-pressure transients
3. design susceptible to pressure transients did not use devices aimed at reducing magnitude of pressure transients

https://www.rhfs.com/pulse/water-hammer-pulsation/



Example waterhammer arrestor design to reduce pressure transient magnitude

Technical Activities

- Assembled a Multi-organizational (NASA, NESC, The Aerospace Corporation) and multidisciplinary team (Structures, Propulsion, Dynamics) to develop recommendations presented in this position paper
- Developed questions, which formed the basis of the recommendations in the paper
- Coordinated across disciplines to provide an integrated recommendation to each question
- Performed extensive literature review on approaches used by aviation, civil, nuclear, and space systems
- Performed numerical case studies to reproduce analyses documented in the literature
- Addressed concerns by team members and external consultants
- Periodic peer reviews of the position paper by the core team/consultants, within each discipline, across disciplines, a pre-NESC review, and formal NESC review
- Multiple rewrites to achieve balanced approach on conflicting technical viewpoints

Multidisciplinary and multi-organization involvement led to a comprehensive consensus position paper that provides recommendations on how to treat pressure transients in pressurized systems

Outline

(1) Physics of transients and the factors that influence them

(2) Strategies to reduce the magnitude of transients

(3) Prediction or measurement of pressure transients (including case studies)

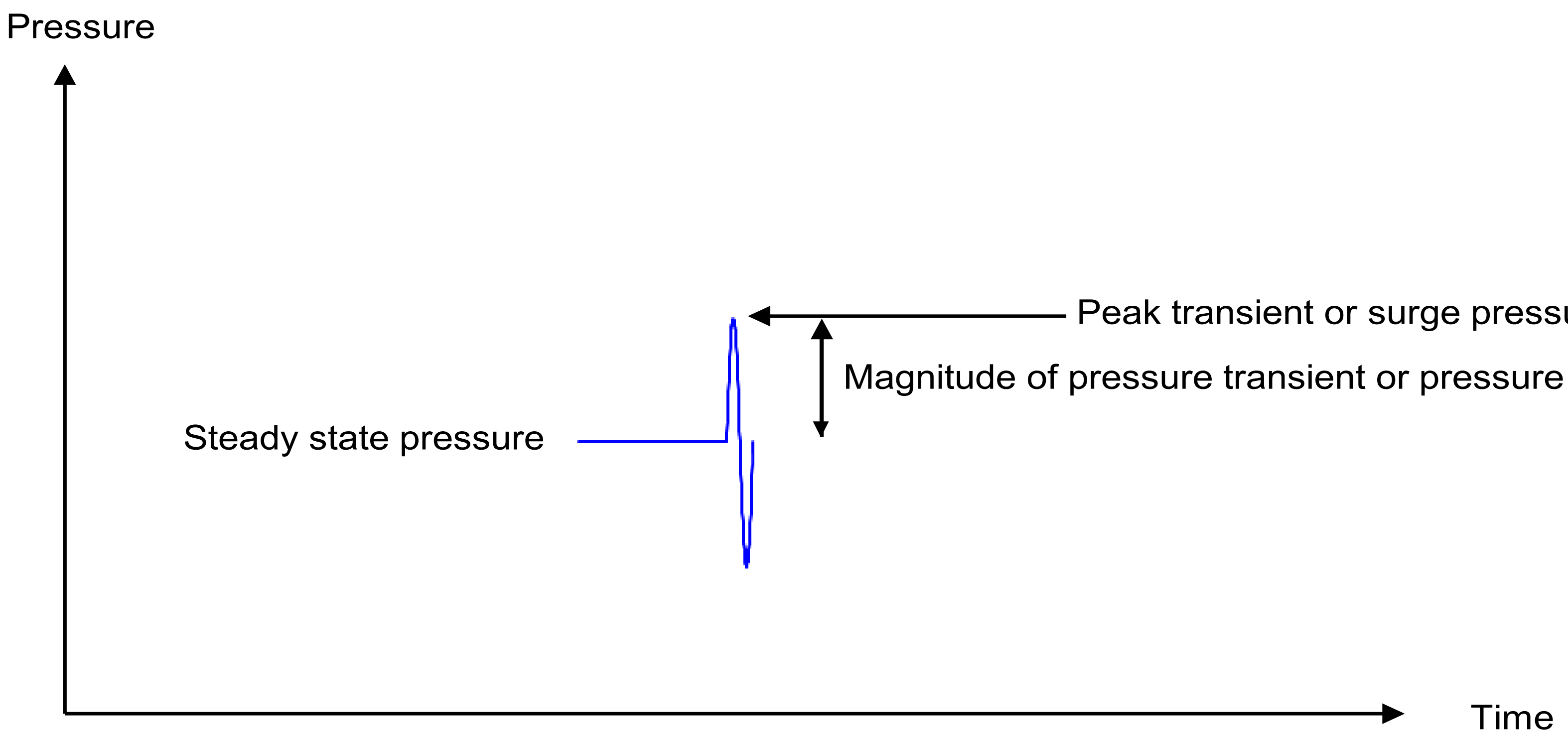
(4) Prediction or measurement of the structural response (including case studies)

(5) Treatment of transients in various aerospace standards

(6) Treatment of transient pressure events in the structural verification

Nomenclature

MEOP – Maximum Expected Operating Pressure
Transient – a dynamic event due to disruption in the flow
Pressure transient – pressure increase above steady state pressure (dynamic pressure response)
Peak transient – Steady state + pressure transient



Transients

- Transients are dynamic fluctuations in pressure caused by valve actuation, fluid system priming, fluid discharge, vibration, and flow disturbances
  - Pressure fluctuations within spaceflight hardware are a regular occurrence

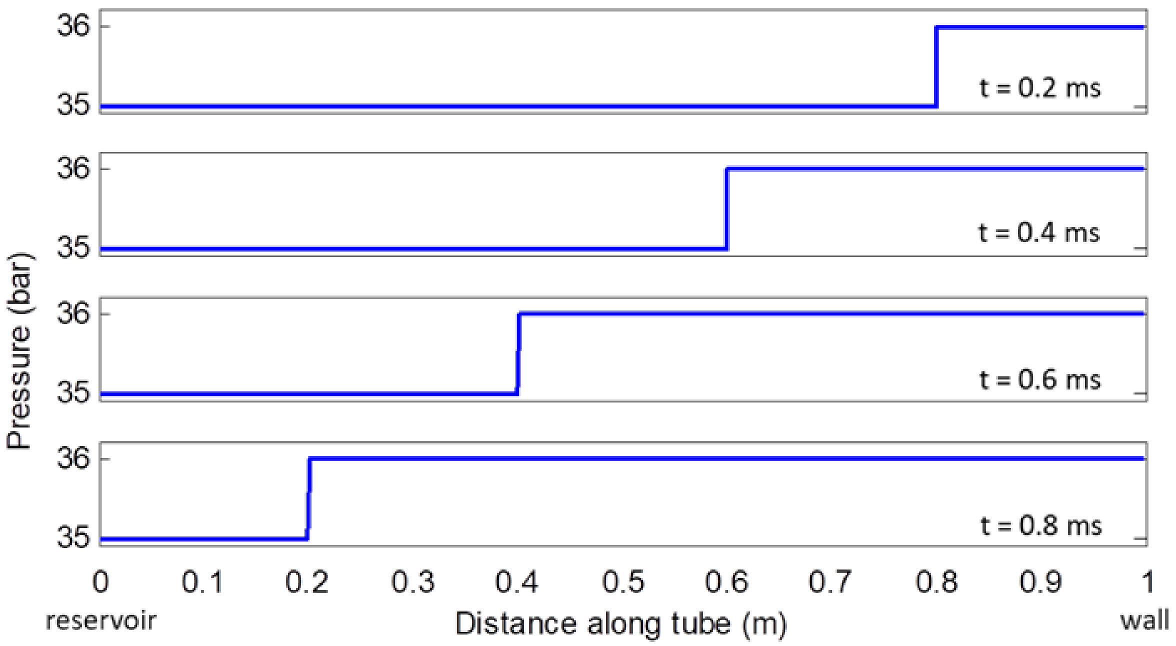
- Transients must be predicted or measured accurately to inform the design

- Sources of failure can be:
  - Analysis that did not include worst-case operating conditions
  - Insufficient design evaluation of elements vulnerable to high-pressure transients
  - Design susceptible to pressure transients did not use devices aimed at reducing its magnitude

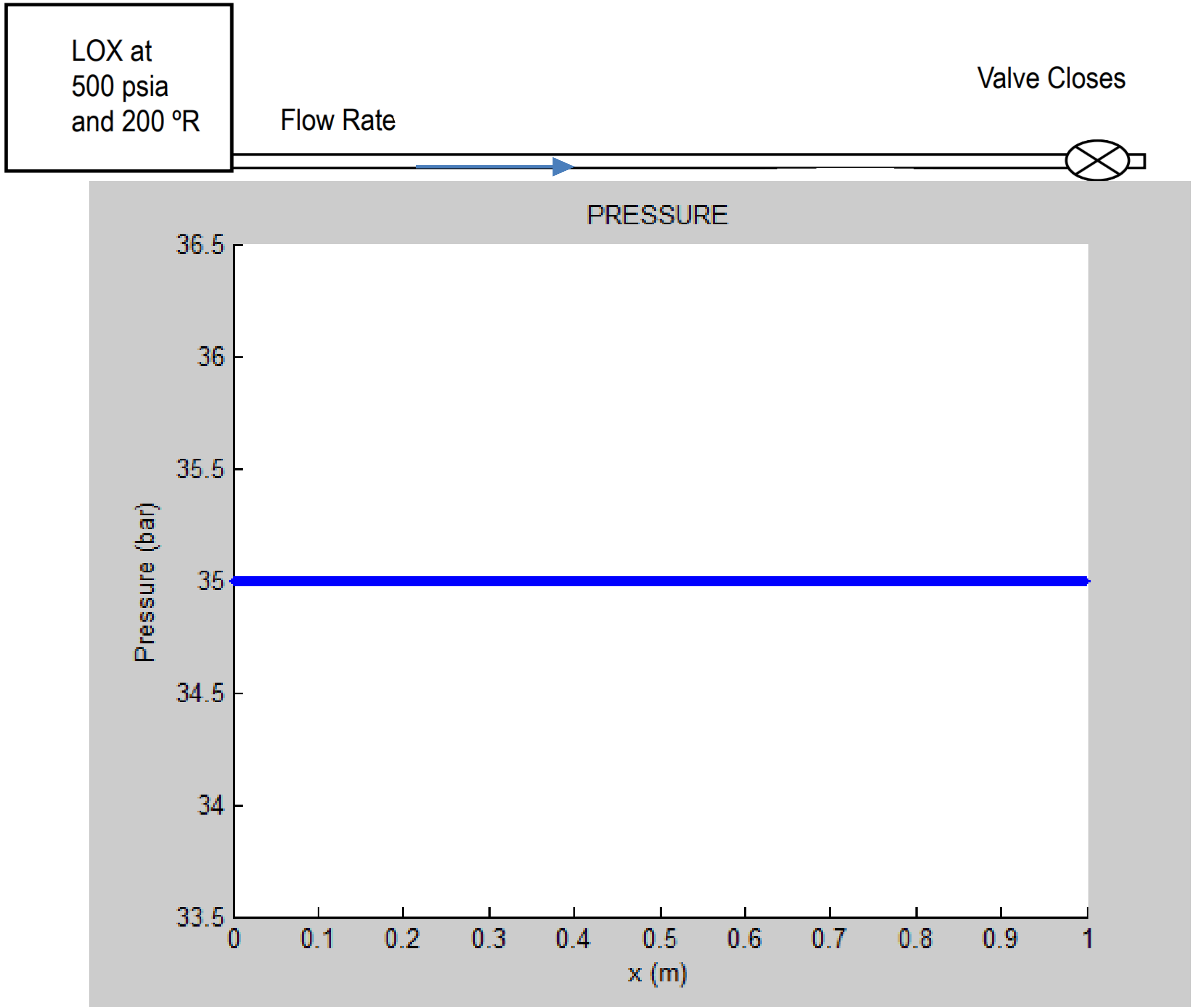
- Analytical and experimental evidence have shown that fast-moving transients can elicit a structural response and should be considered in the verification process

Physics of Transients

- Reservoir-Pipe-Valve (RPV) model demonstrating transient
- Initially steady-state outflow from reservoir & valve closes suddenly
- Pressure wave originates at valve and initially travels upstream to reservoir (right to left)



Physics of Transients

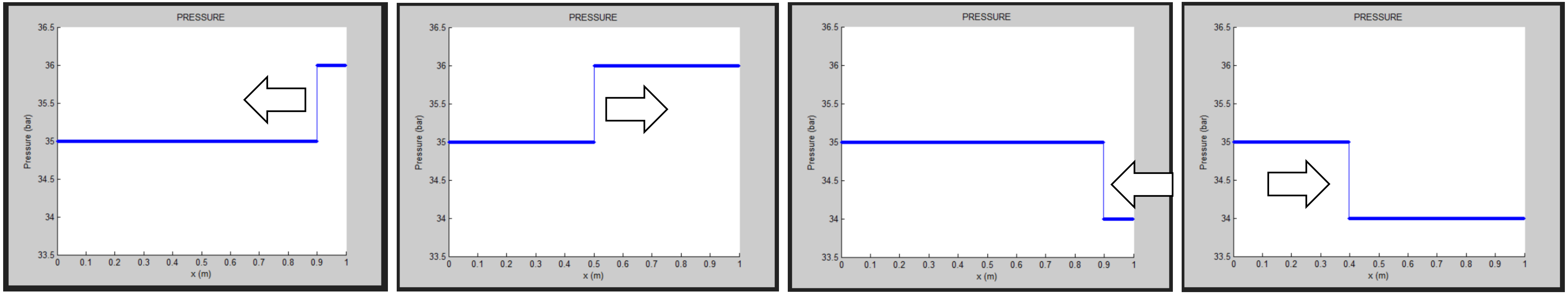


Physics of Transients

- The origination and completion of one full pressure wave from sudden valve closure contains two expansion wave “pulses” and two contraction wave “pulses”

- The pressure wave originates from the fluid having to satisfy a zero-velocity boundary condition imposed upon the fluid from the valve closure

- Wave propagation occurs at the sound speed of the fluid and continues until steady-state pressure is achieved (either from frictional line losses or losses from components)



Factors Influencing Transients

- **Valve Closure Time**
  - Dictates the rate of change in momentum of the fluid
  - More rapid valve closure results in narrower wave front and larger magnitude of compressive wave front
  - “Instantaneous” valve closure means that closure time is significantly faster than the time it takes for the pressure wave to propagate through the pipe and readjust flow

- **Pipe Network Configuration**
  - Orientation of pipe axis with gravity can influence severity of pressure transient magnitude due to pressure head, specifically for large pipe diameters and long pipes
  - Branch configurations can cause pressure waves to constructively interfere with structural modes

- **System Level Fluid Dynamics**
  - Thruster pulsing for attitude control is common application
  - If thrusting frequency lines up with the frequency content of transients, then resonance may result in larger pressure spikes

Factors Influencing Transients (cont'd)

- **Fluid Compressibility**
  - Degree of compressibility directly influences magnitude of pressure spike because transient is proportional to fluid density
- **Structural Characteristics**
  - Magnitude and frequency characteristics of the transient are affected by the structural rigidity of the tubing through which the fluid travels
- **Damping**
  - Dissipates energy within the fluid and (somewhat) within the structural components
- **Fluid Storage Vessels**
  - Composite overwrapped pressure vessels (COPVs), metallic pressure vessels (MPVs), and pressurized structures are considered fluid storage vessels based on the relationship between their relatively large storage volume and the comparably small cross-sectional area of the inlet and outlet tubing in the systems they supply
  - Transients typically have minimal impact on these storage hardware / reservoirs

Outline

(1) Physics of transients and the factors that influence them

(2) Strategies to reduce the magnitude of transients

(3) Prediction or measurement of pressure transients (including case studies)

(4) Prediction or measurement of the structural response (including case studies)

(5) Treatment of transients in various aerospace standards

(6) Treatment of transient pressure events in the structural verification

Mitigation of Transients

- **Valve Closure Schedule**
  - Optimize relative timing of valve closures avoid resonance

- **Orifices**
  - Orifices and cavitating venturi can be used to reduce overpressure at experienced upstream components but at the cost of added pressure losses during operation

- **Check Valves**
  - Can act to isolate the pressure wave created downstream of the check valve from sensitive components upstream
  - Closure of check valve itself may generate a pressure wave which must be accounted for
  - Stagnant fluid between check valve and pipe’s end is hydraulically locked

Mitigation of Transients

- **Pressure Relief Valves**
  - Way of directing pressure overboard rather than allowing it to move upstream
  - As with check valve, response time must be assessed, and fluid expulsion must be given consideration

- **Accumulators**
  - Type of surge volume that reduces magnitude of pressure fluctuations by absorbing much of incoming wave
  - Can be placed in line or out of line, but can be large in size and must be traded against weight and available space limitations

- **Piping Design**
  - Correct selection of pipe diameter, thickness, span length, junctions, etc. can influence transients

Outline

(1) Physics of transients and the factors that influence them

(2) Strategies to reduce the magnitude of transients

(3) Prediction or measurement of pressure transients (including case studies)

(4) Prediction or measurement of the structural response (including case studies)

(5) Treatment of transients in various aerospace standards

(6) Treatment of transient pressure events in the structural verification

Characterization of Pressure Transients

- Design of any pressurized system should be accompanied by a fluids analysis or test to characterize the pressure transients and verify controls used to limit pressure transients

- Three methods can be used to characterize pressure transients
  1) Joukowsky Equation (tends to be conservative except in few cases)

$$\Delta P = \rho \frac{\left(\frac{\beta}{\rho}\right)^{\frac{1}{2}}}{\left(1 + \frac{\beta}{E}\frac{D}{t}C\right)^{\frac{1}{2}}} \Delta V$$

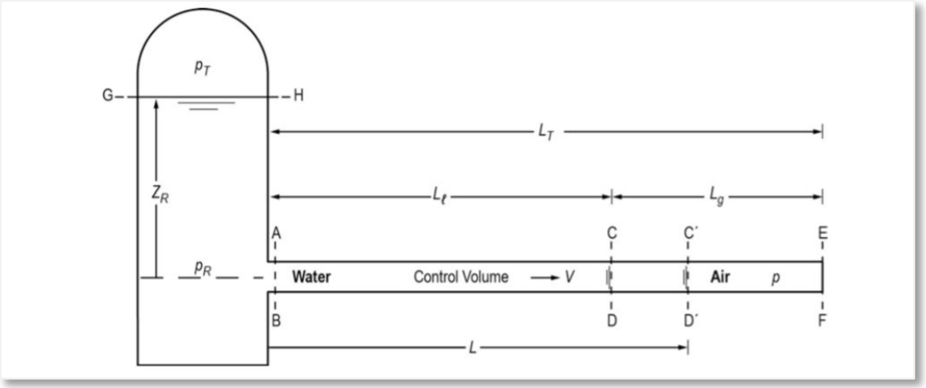
ΔP is pressure transient, ρ is fluid density, a is wave speed, and ΔV is the change in velocity β is the fluid bulk modulus, E is pipe elastic modulus, D is inner diameter of the pipe, t is pipe thickness, and C is the boundary factor, which depends on Poisson's ratio

  2) Advanced transient fluid models for analyzing steady-state and dynamic flow networks (e.g., NASA Generalized Fluid Systems Simulation Program (GFSSP), Aerospace LPTC)

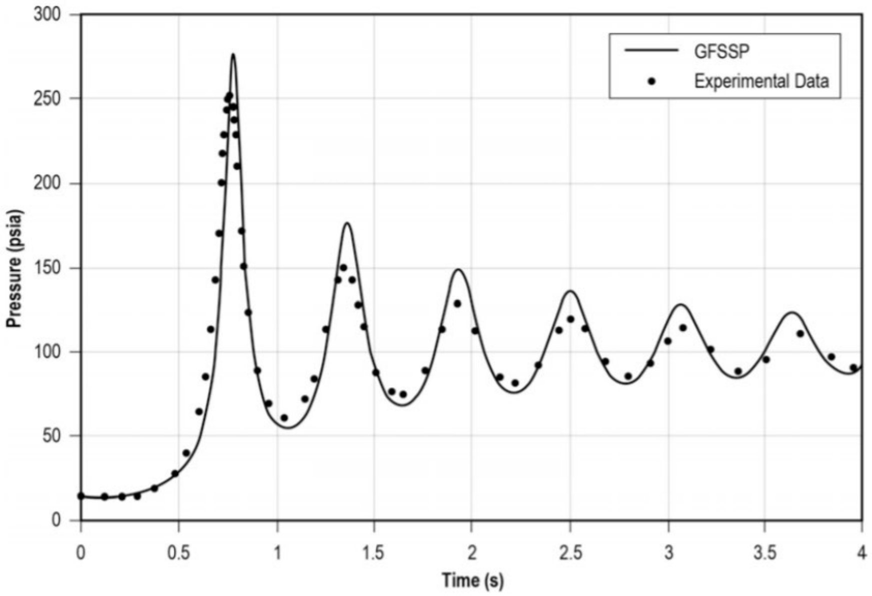
  3) Alternatively, test or flight instrumentation can be used to characterize the system pressure transients

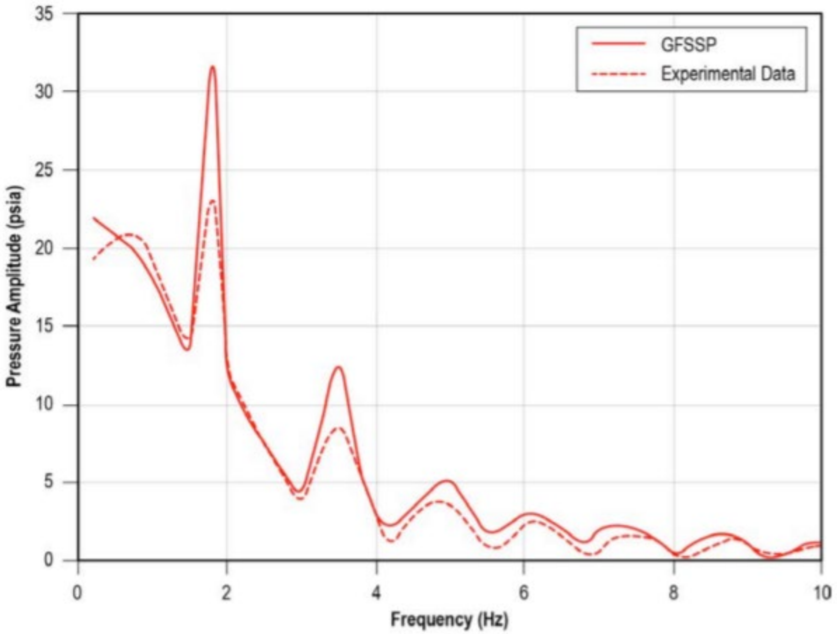
Advanced Transient Fluid Models

- Consider the Reservoir-Pipe-Valve model but a portion of the pipe containing entrapped air and the system was being subject to sudden valve opening



- Analytical prediction capabilities of GFSSP demonstrate good agreement with experimental data the exemplar case (among many others)





Measurements of Pressure Transients

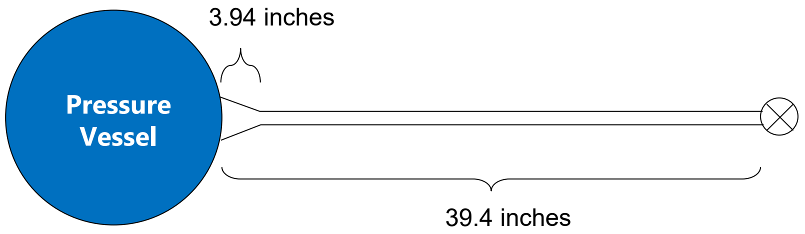
- Subsystem tests can be performed using Test-Like-You-Fly (TLYF) principles that incorporate operational aspects (e.g., valve closure schedule)

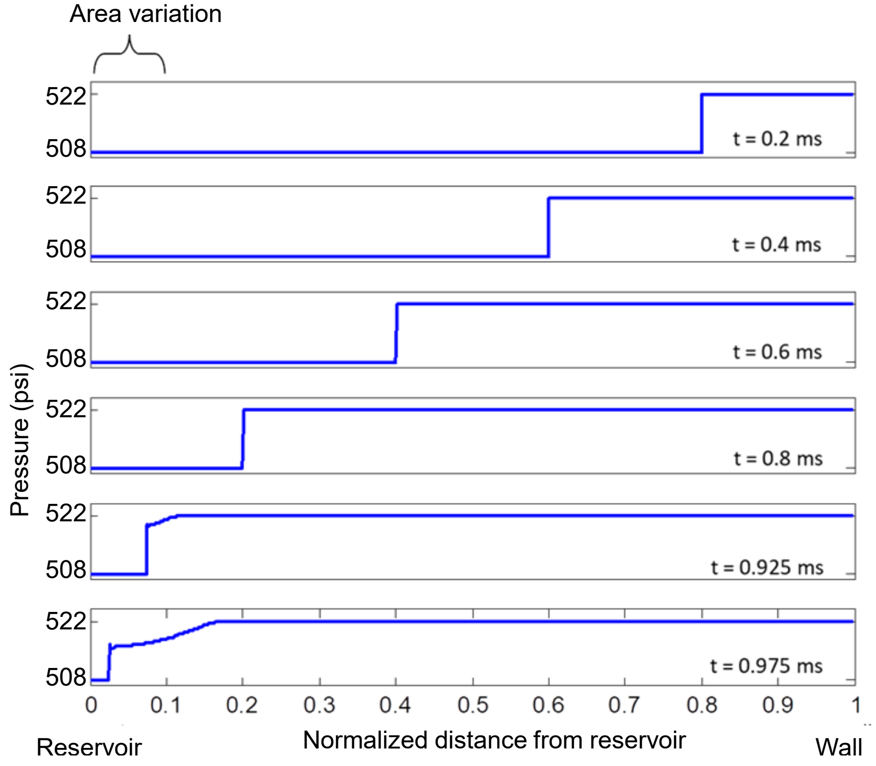
- Test hardware is usually instrumented with pressure transducers to characterize the behavior of pressure transients

- Another approach that has been used is to gain an additional understanding of the system during flight tests, but a failure event can lead to expensive redesigns

Pressure Transients in Vessels

- Transient pressure events usually have minimal impacts on fluid storage vessels (MPV's, COPV's, Pressurized Structure, accumulators, etc.)
- A fluid storage vessel is large in comparison to inlet geometry, and so an approaching pressure wave dissipates quickly within the structure
- As a fluid wave goes from a pipe into a large plenum, the energy of the wave dissipates with the inverse of the square of the distance ($1/r^2$).
- 1D fluid transient analysis with a flare transition to a vessel predicted a 50% drop in pressure within the flare, supporting the assumption that pressure drops fairly rapidly into the vessel
- Fluid storage vessels are mathematically represented as boundary conditions that force the pressure to remain steady, so there are no transients.





Outline

(1) Physics of transients and the factors that influence them

(2) Strategies to reduce the magnitude of transients

(3) Prediction or measurement of pressure transients (including case studies)

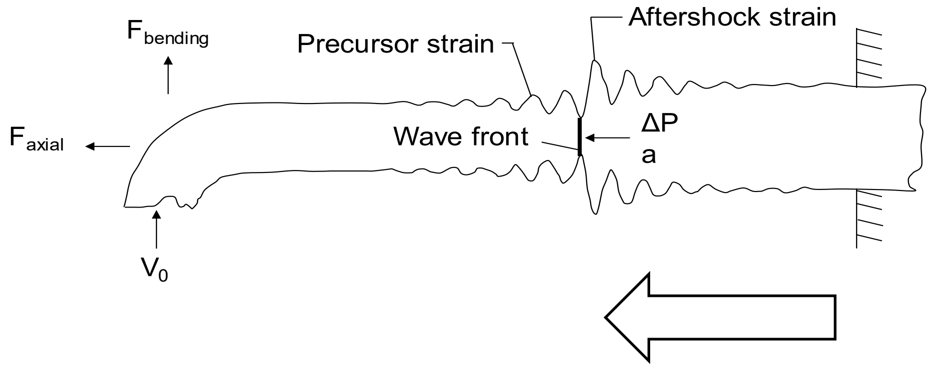
(4) Prediction or measurement of the structural response (including case studies)

(5) Treatment of transients in various aerospace standards

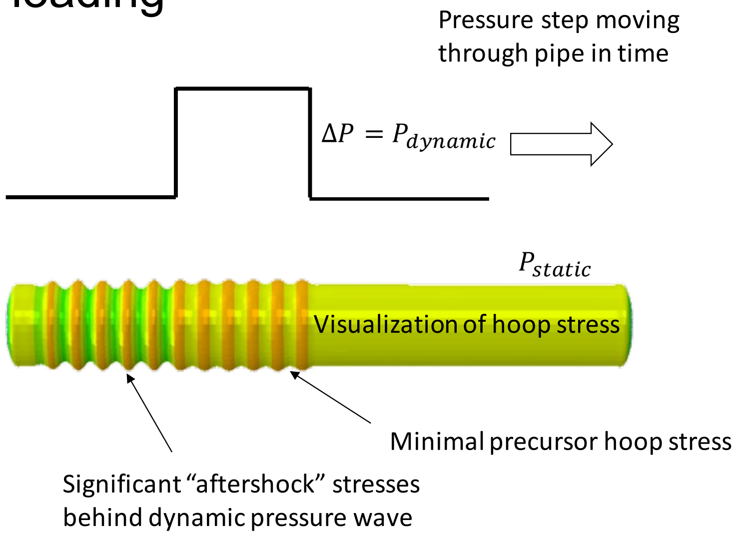
(6) Treatment of transient pressure events in the structural verification

Dynamic Structural Response

- Structural response due to pressure transients can be predicted using finite element analysis or measured by test
- Pressure oscillations cause stress oscillations. Oscillations can occur at frequencies that coincide with the natural frequencies of the structure, thus setting up a resonant condition where stress magnitudes can increase with each oscillation
- The traveling pressure wave front causes precursor and aftershock stresses and strains in the pipe wall due to the localized bending moment caused by the sudden loading



Concept drawing of precursor and aftershock strains and respective wavefront. Wave direction right to left.



FEA post-processing of single time step showing aftershock hoop stresses for traveling square wave. Wave direction left to right.

Dynamic Amplification Factor

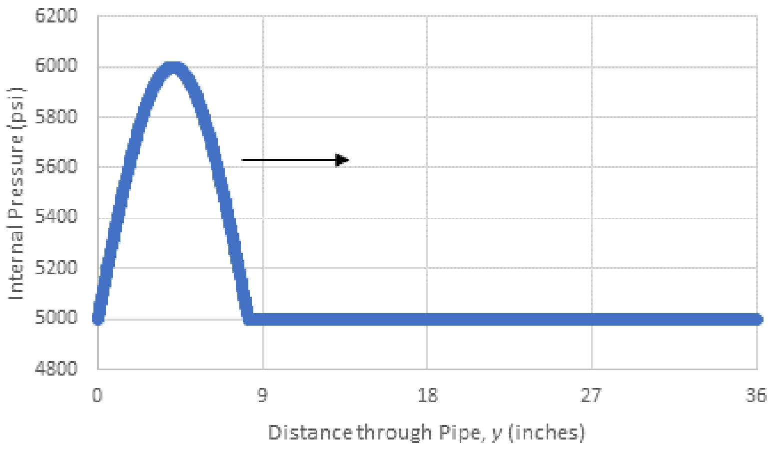
- **Dynamic Amplification Factor (DAF)** is an approach to account for the structural response due to pressure transients
- DAF scales the static pressure load in a static analysis to produce a stress level equivalent to that obtained by a dynamic analysis
- DAF is defined as the ratio of stress obtained dynamically to that obtained statically

$$Dynamic\ Amplification\ Factor\ = \frac{Dynamic\ stress\ caused\ by\ pressure\ transient\ increase}{Static\ stress\ when\ pressure\ increase\ acts\ statically}$$

- DAF factor helps characterize the structural response:
  - Pressure transient event occurs slowly: Structure will likely react statically (DAF~1)
  - Pressure transient is very fast: Structure will not react to the transient (DAF~0)
  - Pressure transient results in a dynamic: amplification above the static response (DAF>1)

Dynamic Structural Response

- DAF depends on pressure transient characteristics (pulse shape and duration), structural characteristics (geometry, materials, boundary conditions), and damping
- A parametric study conducted illustrated generation of a design curve for DAF
  - Simulated moving pressure wave across the tube in 3D
  - 7 relevant parameters were varied, with E as modulus, ρ as density, r as radius, ω as the forcing frequency
- Study concluded that the DAF ranges from zero to values greater than unity; consistent with the literature

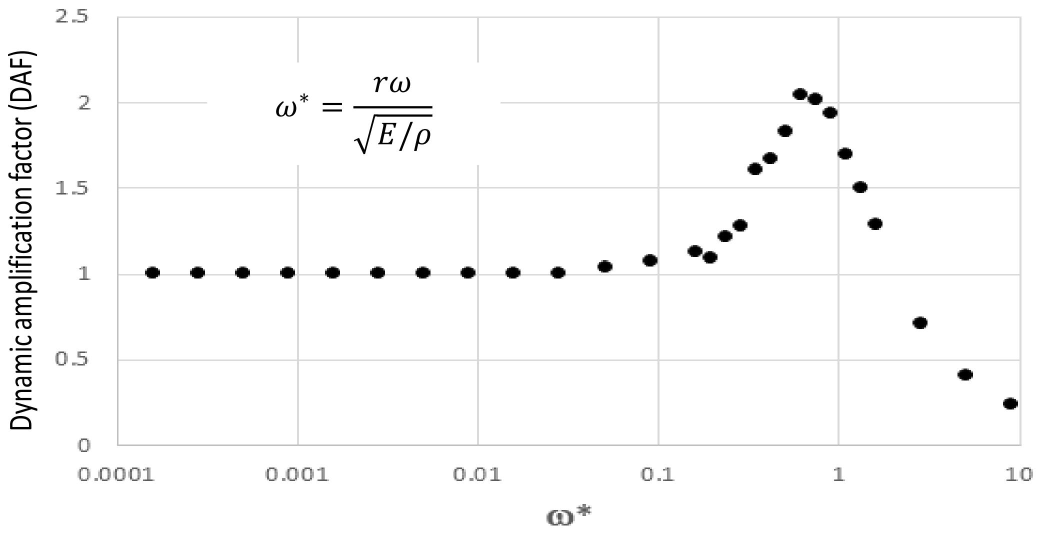


Physics explanation

$\omega^* \ll 1$ is similar to static load, so DAF=1

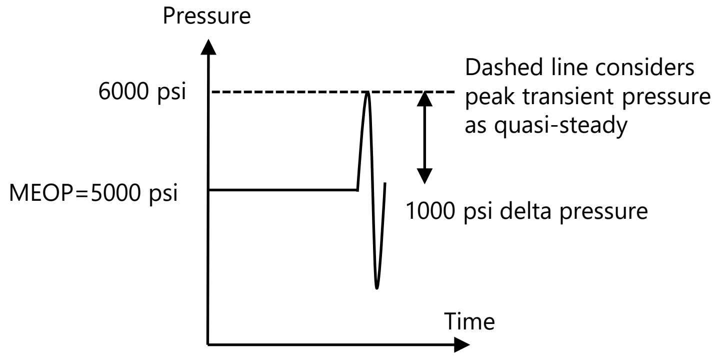
$\omega^* = 1$ has resonance and max DAF of ~2 for this case study

$\omega^* \gg 1$ means the structure responds slower than the load and has DAF ~ 0



Dynamic Amplification Factor Calculation

- **Example: Tube with steady state pressure of 5,000 psi and a pressure transient of 1,000 psi**



- Assume the following:
  1. Peak stress from 5000 psi quasi-static pressure = 10 ksi (QS5)
  2. Peak stress from 6000 psi quasi-static pressure = 12 ksi (QS6)
  3. Peak stress from 5000 psi dynamic pressure = 10 ksi (D5)
     - Pressure is static, so no amplification
  4. Peak stress from 6000 psi pressure waveform = 14 ksi (D6)
     - Includes 5000 psi quasi-static and 1000 psi pressure transient
  5. Peak stress from 1000 psi delta pressure transient = 4 ksi (D1)

Two ways to calculate DAF:

- **Method 1** (*works for linear and nonlinear systems*)
  - Stress from 5000 psi quasi-static pressure → QS5
  - Stress from 6000 psi quasi-static pressure → QS6
  - Stress from 5000 psi dynamic pressure → D5
  - Stress from 6000 psi dynamic pressure → D6

$$DAF = \frac{(D6-D5)}{(QS6-QS5)} = \frac{(14-10)}{(12-10)} = 2.0$$

- **Method 2** (works for linear systems only)
  - Stress from 5000 psi quasi-static pressure → QS5
  - Stress from 6000 psi quasi-static pressure → QS6
  - Stress from 1000 psi pressure transient → D1

$$DAF = \frac{(D1)}{(QS6-QS5)} = \frac{(4)}{(12-10)} = 2.0$$

Evaluation of DAF removes ambiguity on subjectively determining effects of "**short pressure transients**"

Measurement of DAF

- Specialized bench tests can be conducted in a test configuration involving a high-pressure fluid storage vessels, pipes, and valves simulating the pressure transient loading

- The test configuration requires instrumenting the part with accelerometers, strain gages, and pressure transducers

- The sampling rate selected should be sufficient to capture the full fluid, dynamic, and structural response to appropriately quantify DAF

- TLYF principles apply and should attempt to induce a pressure transient in a flight-like hardware configuration in terms of fluids, geometry, length, materials, and other relevant materials

- These tests provide data to benchmark analysis approaches and the data can be used to conduct sensitivity studies relative to effects of valve closure characteristics on the resulting structural dynamic amplification

Outline

(1) Physics of transients and the factors that influence them

(2) Strategies to reduce the magnitude of transients

(3) Prediction or measurement of pressure transients (including case studies)

(4) Prediction or measurement of the structural response (including case studies)

(5) Treatment of transients in various aerospace standards

(6) Treatment of transient pressure events in the structural verification

Survey on MEOP

- **AIAA-S-080A:**

  Requires MEOP be **considered** by system analysis that accounts for effects of temperature, <u>transient peaks</u>, vehicle accelerations, and relief device tolerance

- **ISO 10786:2011**

  States that MEOP **include** the effects of temperature, <u>transient peaks</u>, relief pressures, regulator pressures

- **NASA-STD-5001B**

  States that MEOP shall **include** the effects of temperature, <u>transient peaks</u>, vehicle acceleration, and relief valve tolerance

Survey on MEOP

- **ECSS-E-ST-32C Rev. 1:**

  Defines MEOP with a note stating that the effect of pressure transient is **assessed** for each component of the system and used to define its MEOP

- **SMC-S-005 (2015):**

  MEOP definition must **include** peak transient pressure except in cases for pressure components where pressure transients persist for only “a fraction of a second”

  Defines peak magnitude of pressure transient as “maximum value of pressure wave … that persists only for a fraction of a second”

- **FAA Advisory Circulars:**

  Require that pressure surges be **considered** from normal operation of valves and orifices in defining “maximum” pressures

  For “design operating pressures,” short-term pressure transients can be excluded from strength assessment but must be considered in the fatigue life assessment

Observations on MEOP

- All standards and regulations require that pressure transients be assessed or considered when defining MEOP; however, there is limited guidance on the treatment of transient pressure events in the structural verification process. What constitutes a transient pressure event whether it is in the order of few milliseconds or 50 milliseconds?

- Some Aerospace programs have either ignored the transient pressure loading (DAF = 0) or added the steady-state pressure to the pressure transient (DAF = 1.0). However, DAF can be greater than 0 and even greater than 1.0

- Standard bus configurations for DoD and NASA programs have not experienced structural failures caused by pressure transients and those programs did not use the DAF concept. Proof (1.5) and burst factors (2.5 or 4.0) applied to the MEOP for pressure components in the structural verification process may have inadvertently protected for the effects of dynamic amplification for cases where DAF was greater than 1

- Recommendation is to define MEOP more rigorously with less subjectivity as to what constitutes a “short duration transient”

Outline

(1) Physics of transients and the factors that influence them

(2) Strategies to reduce the magnitude of transients

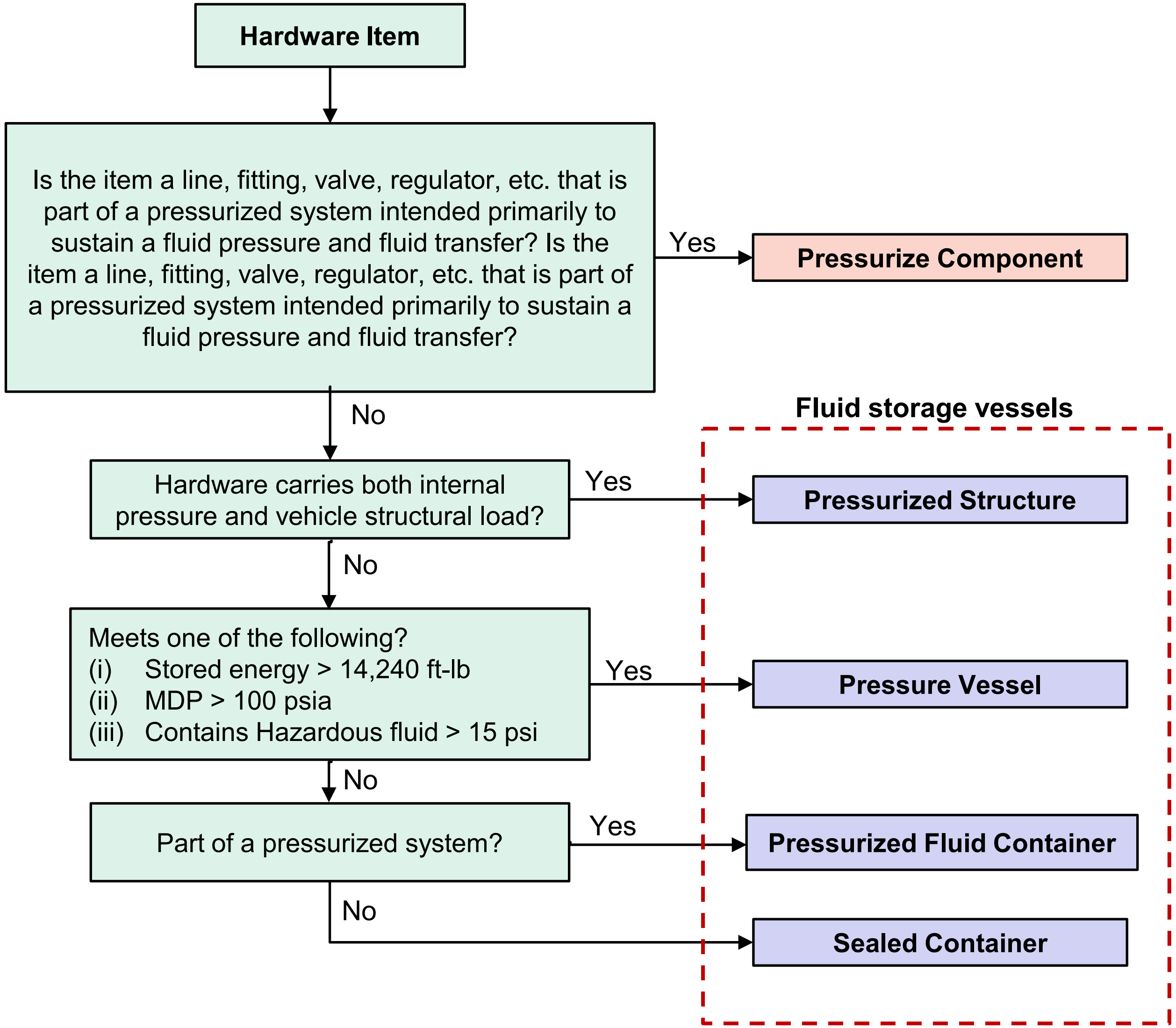
(3) Prediction or measurement of pressure transients (including case studies)

(4) Prediction or measurement of the structural response (including case studies)

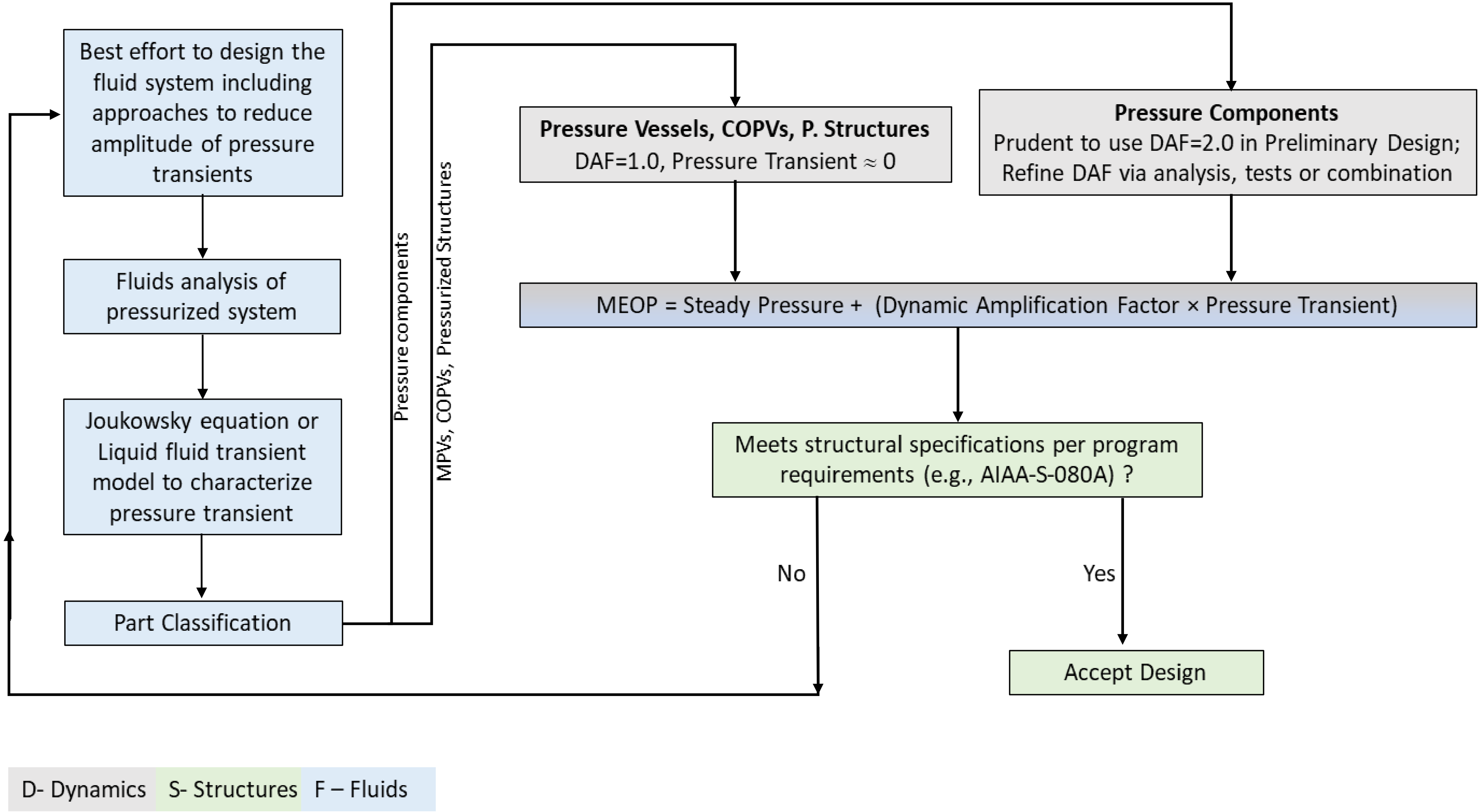
(5) Treatment of transients in various aerospace standards

(6) Treatment of transient pressure events in the structural verification

Classification of Pressurized Hardware



Workflow for Transient Pressure Evaluation



Pressure Vessel MEOP Recommendation

- Magnitude of the pressure transient is ~ zero since the pressure wave dissipates rapidly as it enters a spacious volume
- Further, no dynamic amplification occurs from a transient into a large spacious volume (DAF~1).
- In most cases MEOP for pressure vessels can be defined as:

$$MEOP = \textit{Steady-state Pressure} + DAF \times \textit{Magnitude of the Pressure Transient}$$

$$MEOP_{PV} \approx \textit{Steady-state Pressure} + 1.0 \times 0.0 = \textit{Steady-state Pressure}$$

- When in doubt a fluid analysis should be performed to predict the pressure transient
- Proof/burst factors in the standards are applied to MEOP to establish test levels

Pressure Component MEOP Recommendation

- Pressure transient magnitude should be estimated using analysis or test
- DAF should be estimated using analysis, test, based on heritage applicable flight-like data. Prudent to use 2.0 if there is lack of information
- MEOP adjusted using the following formula:

$$MEOP = \text{Steady-state Pressure} + DAF \times \text{Magnitude of the Pressure Transient}$$

- Proof/burst factors in the standards can be applied to MEOP to establish test levels
- Structural verification approaches:
  - No damage tolerance approach uses the standard proof/burst factors in standards
  - Damage tolerance approach uses the lower proof/burst factors that can result in weight savings, especially when DAF or pressure transient is significant

Illustrative Case Study

Case	Static Pressure	Pressure Transient	DAF	MEOP	Proof Pressure	Burst Pressure
A - Preliminary design DAF, Joukowsky equation	190	1610	2	3410	5115	8525
B - Predicted DAF, Joukowsky Equation	190	1610	1.2	2122	3183	5305
C- Predicted DAF, MOCs	190	202	1.2	432	648	1080

- Conditions: Steady state pressure - 190 psi
  - Pressure transient estimate using Joukowsky Equation is 1610 psi and 1D fluid model is 202 psi

- Increasing levels of analysis fidelity to refine DAF and pressure transient, results in in lighter weight designs (DAF in this example was calculated as 1.2)

- MEOP, proof Pressure, and burst pressure can be calculated based on the DAF
  - Assuming proof factor of 1.5 and burst factor of 2.5 per AIAA-S-080A for pressure components

- For a 2-inch-diameter tube made of aluminum, the wall thickness required to maintain positive ultimate margin for Case A would be 0.189 inch whereas for Case C would be 0.024 inch, resulting >8x reduction in required mass

Illustrative Case Study

Case (psi)	Static Pressure	Pressure Transient	DAF	MEOP	Proof Pressure	Burst Pressure
A - Preliminary design DAF, Joukowsky equation	190	1610	2	3410	3751	4774
B - Predicted DAF, Joukowsky Equation	190	1610	1.2	2122	2334	2971
C- Predicted DAF, MOC	190	202	1.2	432	475	605

- USSF/The Aerospace Corporation uses a damage tolerance approach by allowing lower proof (1.1) /burst factors (1.4); this can enable additional mass savings when pressure transients or DAF is significant

- This approach has not been adopted broadly by NASA, but warrants further study by the Agency

Notable Peer Review Comments

- Comment #1: Definition of MEOP is an interdisciplinary subject, not just one discipline involvement

  Response: “The design of a pressurized system is complicated and requires an iterative process across disciplines. Therefore, communication across disciplines is paramount in ensuring the pressurized system is robust.”

- Comment #2: DAF = 2.0 at the preliminary design stage can be too penalizing

  Response: “… if the frequency content of the pressure transient is much greater than any of the structural frequencies, then the DAF is likely much less than 1.0. Applicable data from heritage systems can be leveraged to estimate DAF. With no information available, it is prudent to use a DAF = 2.0 in the preliminary structural design process as many structural analysis and experimental observations indicate a DAF of 2.0.” “Design curves can be developed to estimate DAF…”

Notable Peer Review Comments

- Comment #3: Short duration transients do not cause structure to respond

  Response: Depends on the pressure transient and structural characteristics involved in the problem. The report provides case studies indicating the structure can respond to fast moving transients in an adverse manner. Rather, than a subjective approach, the DAF is used to determine whether the structure responds.

- Comment #4: MEOP should not be adjusted using DAF

  Response: Majority of the reviewers embraced this approach. The report provides the alternative of modifying proof/burst test levels instead of modifying the MEOP.

Notable Peer Review Comments

- Comment #5: Applying DAF can be overly penalizing in terms of weight

  Response: A DAF greater than 1.0 implies that the structural response is amplified above a static response and should be considered in the structural evaluation rather than dismissing it.

  The USSF and The Aerospace Corporation uses a damage tolerance approach with lower proof/burst factors that can be used in cases where the pressure transient and the DAF are significant.

Notable Peer Review Comments

- Comment #6: Standard bus configurations for DoD programs have been successful without the use of the DAF concept.

  Response: “Standard bus configurations for DoD programs have been successful without the use of the DAF concept. The DAF may have been less than 1.0 or the proof and burst factors specified in AIAA-S-080A for pressurized components may have inadvertently protected components from failure. New applications deviating from standard bus heritage practices require an understanding of the DAF.

  When a program elects to allow the peak pressure transient to exceed the proof pressure or the DAF concept is not adopted, then risk mitigations need to be put in place which can include robust qualification test program, analysis, inspections, and adopting designs that are not susceptible to workmanship issues.”

- Comment #7: Develop part classification and workflow to walk an engineer through all the steps

  Response: Section 11 and the flowcharts presented earlier were developed to guide the engineer in a step-by-step process.

Summary

Position paper provides a roadmap to simplify treatment of transients in pressurized systems for all future spaceflight hardware;

- Physics of transients, contributing sources, and major influencing factors in pressurized systems (e.g., valves, lines, pressure vessels, pressurized structures) are discussed.
- Mitigation strategies to reduce the magnitude of pressure transients during design phase.
- **Distinction between Fluid response vs. Structural response**.
- Fluid analysis techniques to predict pressure transient with case studies.
- **Introduction of Dynamic Amplification Factor for structural response.**
- **Classification of Pressure system components to ease the burden on programs**.
- The treatment of pressure transients in the structural verification process.

Backup

Compelling Reason

- This NESC task was initiated at the request of the CCP chief engineer, to remove the ambiguity on how to treat pressure transients in spaceflight hardware
- Hardware developers try to bypass this assessment to save time and effort (experienced by ISS, CCP, COPV PVWG, NESC, and HLS D&C programs)
- Pressure transients have led to propulsion/structural issues in flight hardware
- Since numerous factors affect transients, a fool-proof approach to treating these is absent
- Confusion, contradiction, and vagueness with pressure system requirements exist amongst several documents discussing pressure related requirements
- This document is an effort to demystify pressure transients and provide a roadmap to simplify treatment of pressure transients in pressurized systems for all future human- and non-human-spaceflight pressurized hardware

Objectives

- Position paper provides a roadmap on how to treat pressure transient events in the structural verification process
- The position paper is organized to address the following objectives:
  1. Explain the physics of pressure transients and the factors that influence them
  2. Discuss implementation strategies to reduce the magnitude of pressure transients
  3. Present methods to predict or measure magnitude of pressure transients (including case studies)
  4. Present methods to predict or measure the amplification of the structural response due to pressure transients (including case studies)
  5. Investigate the treatment of pressure transients in various aerospace standards
  6. Develop approach on how transient pressure events can be accounted for in the structural verification process

Provide a comprehensive roadmap on how to treat pressure transients in the structural verification process

Project Timeline

Aug | Sep | Oct | Nov | Dec | Jan | Feb

Kick-off

Kauser/Team develop questions to guide position paper

Aerospace presents SMC-S-005 approach and several briefings on pressure transients

Team completes review of FAA approach

1st white paper draft

Extensive discussions on:
1. Short duration transients
2. Survey of industry failures
3. Aerospace DT approach for pressure components challenged

2nd white paper draft

Team requests:
1. Numerical case studies for pressure transients in vessels and pressure components
2. Literature review on nuclear and civil industries
3. Flow chart providing roadmap

3rd white paper draft

Teams recommends:
1. Re-write and re-organization
2. Adopt DAF to define MEOP
3. Dynamics recommended steps to develop DAF; consistent with literature
4. Peer review of case studies

Propulsion/fluids team send response
1. MEOP should not be increased for short duration transients as they don't produce structural response
2. "No satellite program includes transients" in MEOP
3. Standards do not require including transients in MEOP, but rather assess it

Structures/dynamics respond to fluids
1. Shall statements do exist on transients and MEOP
2. DAF allows assessing transient effects on structure and is consistent with other industries

Structures/dynamics respond to fluids
1. Structures/dynamics argue over DCF, DLF, and DAF terminology
2. Dynamics wants POGO excluded from pressure transient discussion

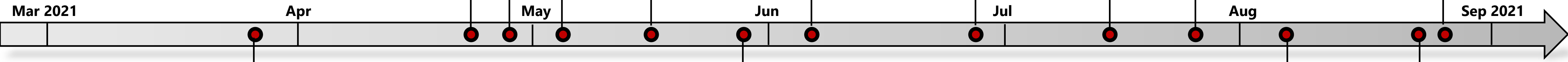
Combined team agrees DAF approach has merit

4th draft; extensive comments from core team

5th draft

Pre-NRB Review
Jeff West
Daniel Dorney
Steve Gentz
Kauser Imtiaz
Eugene Ungar

Project Timeline



Extensive comments received from pre-NRB reviewers:

1. DAF concept well-received by reviewers
2. Provide more application examples
3. Audience of paper is unclear
4. Illustrate pressure transients with graphics
5. Convince designers pressure transients are real
6. Discuss test-based approaches
7. Improve clarity in first third of paper
8. "Short duration transients" are arbitrary as defined in industry, explain how DAF can help
9. Improve readability by simplifying sentences
10. Re-organize paper – start from basics; improve flow
11. Add definitions, acronyms, appendices
12. Consistent use of "pressure transients"

6th draft:

1. Extensive re-write and organization
2. 90%+ recommendations accepted
3. Equation derivations moved to Appendix
4. Streamlined content and organized approach for pressure components versus pressure vessels
5. Consistent use of pressure transient across paper
6. Created new application examples

Core team recommends paper cannot be released until another review round and to circle back with Dynamics/Fluids

Core team requests organizational and technical recommendations

7th draft

"Final" team meeting results in additional actions:

1. DAF can result in heavier designs, consider highlighting DT approach with lower factors of safety
2. Add examples on the DT approach
3. New examples showing how MEOP is calculated
4. Create a roadmap chapter that shows how to deal with pressure transients beginning to end
5. Add flowchart on how to classify pressurized systems
6. Explain challenges structural engineers will face when MEOP does not include transient effects
7. Consider alternative approach to evaluate pressure transients other than adjusting MEOP
8. Explain flow of information amongst disciplines
9. Provide data needs for pressure transient assessment

8th draft: team requests internal and cross-disciplinary review

Fluids/propulsion team:

1. DAF can be mistaken as a pressure rather than stress response
2. DAF = 2 for initial design too prescriptive
3. DoD heritage systems with peak pressure < proof without adjusting MEOP have not exhibited failures
4. Improve pressure transient nomenclature with graphics and examples

Dynamics/Structures/Fluids iterate to address concerns by Fluids/Propulsion: triggers another team review cycle

9th draft for NRB review

Addressed 95%+ significant comments from 8 reviewers:

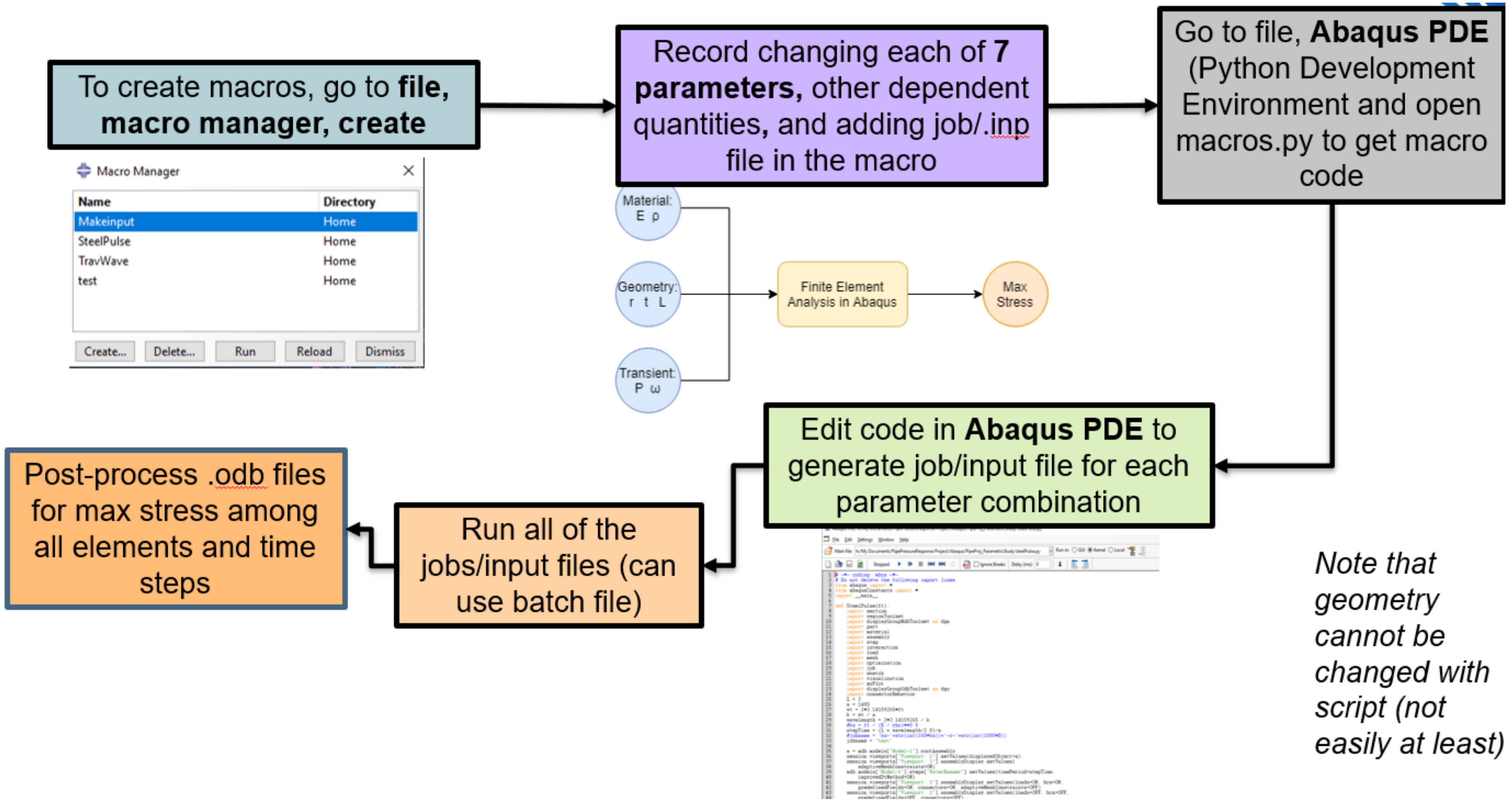
1. Reviewers were complementary of the effort / paper
2. 1/8 reviewers against adjusting MEOP using DAF: reiterated alternate approach to adjust test levels without modifying MEOP
3. Adopted additions for mitigating pressure transients
4. Clarified differences amongst DAF/MUF/DUF
5. Addressed heritage systems where peak pressure exceeded proof
6. Employed unit consistency across position paper
7. Many in-depth questions and re-writes addressed
8. Provided consistent nomenclature and terminology

Team agrees comments were addressed

10th Final Release

Dynamic Structural Response

- Design curve was generated by performing many Abaqus analysis varying pressure characteristics and geometric/material parameters and using an automated python script to extract stresses to compute DAF



Note that geometry cannot be changed with script (not easily at least)